Super Photon Counters

John Mather

The perfect photon detector would measure the arrival time, the energy, the polarization, and the position of every arriving quantum, but that is easier said than done. Two groups have now succeeded in doing time-resolved spectroscopy on the Crab Nebula pulsar, measuring everything but the polarization, with reports from Romani et al. at Stanford[1] and from Perryman et al. at ESTEC.[2] Both groups use superconducting detectors to gain the necessary speed and sensitivity. The photon can heat the electrons in a superconductor biased in the middle of its resistive transition, or break bound superconducting electron-hole pairs, which can then be collected.

Three years ago, Peacock et al. reported[3] that they had detected single optical photons with a superconducting tunnel junction (STJ), and Paresce wrote a News and Views article[4]. A tunnel junction uses two pieces of conductive material, separated by a tiny gap of insulating material or even vacuum. If the gap is thin enough, electrons can tunnel across anyway, and if the conductors are superconductors, the junction displays very useful quantum mechanical properties and electrical nonlinearities. Amplifiers, detectors, oscillators, and computer circuits can all be made from them. Their special advantage is that they operate at very low temperatures, dissipate very little power, operate very fast, and are very small.

Superconducting tunnel junction detectors for visible light were proposed for use on the Hubble Space Telescope, and developed by the European Space Agency group at ESTEC in Noordwijk. This year, Perryman et al.[2] gave the ESTEC group's first astronomical result from their 6x6 STJ array camera mounted on the William Herschel Telescope on La Palma. Considering that each one of the 36 detector elements requires an amplifier and a pulse height analyzer, this was no small feat. The natural target demanding microsecond time resolution is of course the Crab Nebula, where a pulsar spins with a rotation period of only 33.5 milliseconds. They reported a light curve for the pulsar over the wavelength range 310-610 nm, based on data acquired over a 10 min interval, with an accuracy of 5 microsec. An improved version of the camera is presently under development.

Now, microcalorimeters can also do the job, as reported by Cabrera et al.[5] and they have been used for measuring the Crab light curves too, according to Romani et al.[1] In this scheme, tiny 18 μm squares of 40 nm thick tungsten, similar in size to individual CCD array pixels, are patterned on a silicon substrate. They are cooled slightly below the 80 mK superconducting transition of the detector elements, using a helium dilution refrigerator. An electrical bias voltage is applied to the superconductor and a current flows. Since the electrical resistance of the superconductor is still not quite zero, the current heats it up a little, quickly reaching a stable equilibrium because the hotter the electrons, the less current can flow. This is a kind of negative "electro-thermal feedback" which speeds up the approach to equilibrium. Now, when a photon hits the tungsten and is absorbed by an electron, the temperature of the tungsten electron system rises a tiny

amount, less current flows through the superconductor, and the change can be measured. The devices are called transition edge superconducting (TES) sensors. They are very sensitive, partly because very small current changes can be measured using a superconducting amplifier known as a SQUID (Superconducting Quantum Interference Device). The Crab light curves from a single detector element are shown in Fig. 1 for 10,000 seconds of data.

Now that practical demonstrations have been made, we can imagine future applications. The ability to measure single photons might well be extended to much longer wavelengths. The tungsten microcalorimeters have an energy resolution reported as 0.15 eV, and are able to detect individual photons with wavelengths up to 4 μm before encountering false alarms from electronic noise. To get much better resolution, the detector would have to be much smaller or much colder, and both are possible. Much smaller microcalorimeters can be coupled to superconducting bowtie antennas, enabling operation at wavelengths much longer than the size of the thermometer. For even longer wavelengths, single photon counting may not be necessary, as the sky is bright from emission from interplanetary and interstellar dust. In that case, the detector sensitivity need only be better than the fluctuations from random arrival of the photons. This already seems nearly feasible with today's technology. At the other extreme, X-ray detectors using semiconductor thermistors instead of TES's have already been built for rockets and satellites, and advanced versions using TES's or STJ's may fly on NASA's Constellation-X or ESA's XEUS missions.[6]

The approach of superconducting tunnel junctions may also be pursued much farther. The invention of the Radio Frequency Single Electron Transistor (RF-SET) by Schoelkopf *et al.*[7] opens the door to counting single low energy photons as well. Schoelkopf's amplifier uses two STJ's in series to sense the voltage on a gate capacitor. It is the electrical dual of the SQUID amplifier, which uses two STJ's in parallel to measure the current in an input inductor. Both the SET and SQUID are quantum mechanical amplifiers with unparalleled sensitivities. The RF-SET uses high frequency (GHz range) excitation to measure the amplified current through the series pair of STJ's, and can now measure the presence or absence of a single electron charge on the gate up to 10^8 times per second. Work is already under way at Yale and NASA's Goddard Space Flight Center to test these devices with tunnel junction detectors for far IR wavelengths of 100 μm or longer. Schoelkopf and Prober at Yale are using RF-SET's to measure the currents in STJ detectors, and a Yale-Goddard-Caltech group will be building a 200-pixel camera for Palomar using STJ's.

It will take yet another level of sophistication to build the circuitry to operate large arrays of superconducting detectors. CCD detector arrays are already commonplace in digital cameras and digital video recorders, and infrared arrays using silicon, germanium, InSb, HgCdTe, and other alloys have also been built. The infrared devices usually have a separate amplifier for each pixel, as well as transistors to apply bias and reset the accumulated charges. Nothing like this level of engineering has yet been done for superconducting electronics, but enough principles are known that there are high hopes. High speed SQUID multiplexers [8], analog-to-digital converters, digital memory devices,